Analysis of the main battery characterization techniques and experimental comparison of commercial 18650 Li-ion cells

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***Abstract*— Over the coming years, major growth in the use of Li-ion batteries is expected, both in electric mobility as well as in stationary applications, be it in self-consumption systems and micro grids or in large renewable power generation plants. The proper characterization of lithium-ion cells is of vital importance for the development of precise models that permit the simulation and prediction of their behavior, so as to suitably configure cell groupings for the resulting battery packs, and to properly select the most suitable cells from the extensive manufacturer offer. In this work, an analysis is conducted of the main techniques used in the literature to characterize batteries. Also, an experimental comparative is carried out on 18650 Li-ion cells from three large global manufacturers, focusing on the primary methodologies used to characterize capacity, internal resistance and open circuit voltage. Finally, the advantages and disadvantages are presented for the methodologies used, based on the experimental results obtained.**

Keywords— ***Battery, Characterization, Electrical energy storage, Lithium ion cell, Renewable energy.***

I. INTRODUCTION

Applications using lithium-ion batteries have become increasingly popular, serving as the best solution in comparison to other energy storing technologies, given their high energetic density, long durability and ability to work at high powers. Over recent years, Li-ion batteries have undergone a significant reduction in manufacturing costs, thus becoming one of the most competitive electrical energy storing technologies on the market. But despite the fact that Li-ion batteries have been used in portable applications since the 1990s, this technology has yet to reach its full potential.

Currently, it is difficult to make a clear comparative of the benefits of different Li-ion cells based only on manufacturer data sheets, since each of these offers functioning characteristics in distinct operating conditions. This is similar to what we find in the literature, where almost all authors work with distinct profiles and conditions, lacking a standardized methodology to characterize the Li-ion cells [1]–[3]. Therefore, characterization results are not typically comparable, since they tend to depend mainly on the charge and discharge profile and temperature. This lack of uniformity has hindered the analysis of the comparison of operational characteristics and features between different Li-ion cells.

Distinct methodologies can be used to characterize Li-ion cells and to obtain their main functioning parameters and characteristics. The methodologies used to offer a detailed and precise characterization of Li-ion cells tend to demand extensive testing times [2]. Other methodologies, however, may offer similar results, although perhaps less detailed and less precise, but with a substantial reduction in the time necessary to complete the characterization tests [3]. This reduction in time is especially significant in the accelerated tests of calendar aging, where these procedures may influence the results that are obtained [4].

Based on the above, this article attempts to analyze and propose test techniques to characterize Li-ion cells that achieve an optimal relationship between the experimentation time used and the simplicity of the characterization. The work is presented as follows: Section II offers a brief description of the main Li-ion cells characterization methodologies found in the literature, as well as the most relevant parameters for cell analysis. Section III analyzes and compares the experimental results obtained for various 18650 Li-ion cells of some of the main global manufacturers (LG, Samsung and Panasonic) based on test type. Finally, in Section IV, the principal results obtained are summarized, as well as the study conclusions.

II. METHODS OF CHARACTERIZATION

When characterizing Li-ion cells, three fundamental parameters are relevant: capacity, open circuit voltage (V_{OC}) and internal resistance (R_i). Both the open circuit voltage and the internal resistance depend on the cell's state-of-charge (*SOC*).

Appropriate cell characterization is essential in order to develop an electrical model that permits the analysis of the Li-ion cell behavior in simulation. This characterization must permit the creation of a simple cell model from which it is possible to simulate and optimize both the battery's size and its management [1]. In order to group together the distinct cells in series and in parallel, thus forming battery packs, it is also necessary to determine the dispersion between the distinct cells when optimally grouped. Finally, in the case of subjecting commercially available cells to a selection criterion, based on the distinct applications and profiles in which they are to be used, a proper previous characterization is essential.

A. Capacity characterization

Capacity may be defined as the quantity of charge that can be stored in a cell. This parameter may, for instance, be related to the autonomy of an electric vehicle, the energy that can potentially be stored in an electric micro-grid, etc.

Generally speaking, tests used to measure capacity consist of a continuous current charge, followed by a constant voltage charge phase until reaching a minimum current (CCCV

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Charge). Next, a discharge is carried out at a constant current until reaching a lower voltage (CC Discharge) [2]. Some authors have used another discharge state in which the discharge is carried out at constant voltage until reaching a pre-established current. The capacity value depends mainly on the discharge current and the temperature. The current value tends to reference the nominal capacity value supplied by the manufacturer of the cell, such that this value is standardized when studying distinct cells. This value is referred to as the C-rate and it is defined as the relationship between the charge or discharge current and the nominal capacity.

In an attempt to establish tests of standard capacity, the International Electrotechnical Commission has published the standard IEC62660-1 [5], in which a C-rate of discharge (CC Discharge) of C/3 was established for electric vehicles, and of 1C for hybrid vehicles at three distinct temperatures: 0ºC, 25ºC and 45ºC. However, cell manufacturers typically referenced the capacity of a cell at a C-rate of C/5 [6]–[8] and at a room temperature of 20–25ºC. In the literature, some authors have established a CCCV discharge to measure capacity, so as to assure that the effect of the internal resistance and temperature are reduced [9], [10].

B. *Internal resistance characterization*

The decrease in internal voltage produced in the battery power terminals when current is requested or supplied tends to be modeled on an internal resistance, R_i. In more complex models, this resistance is modeled using an impedance formed by distinct groupings in series and in parallel, of various resistors and capacitors [11], [12].

More complex models require the use of characterization methods such as the impedance spectroscopy test or pulsed multisine test [13]. However, in this work, these methods are not analyzed.

The simplest form of obtaining R_i is based on introducing a current step (ΔI) generating a voltage drop (ΔV). So, according to Ohm's law, $R_i=(\Delta V)/(\Delta I)$. The R_i value depends on the duration of the step. The instantaneous decrease in voltage is related to the cell's ohmic resistance, generated mainly by the opposition of the diverse materials forming the cell upon the circulation of the ionic and electronic charges. Later, the electro-chemical effects of the activation and the mass transport phenomena overlap. In this type of tests, it is quite difficult to differentiate between these effects. Activation processes have time constants of between 1 ms and 30 s, whereas the mass transport phenomena have time constants that exceed 0.1 s and can extend to several hours [10], [11]. The overall decrease in voltage is the total of the three effects. However, it is only possible to differentiate between the decrease in voltage associated with the ohmic effects (ΔV_1) and the total of the decrease in voltage associated with the activation and mass transport phenomena (ΔV_2) as shown in Fig. 1. If the pulse is too long, the cell's charge state will be different from the initial one, therefore it will not maintain the *SOC* and temperature equilibrium state.

The IEC62660-1 standard details how to carry out these pulse tests. It is necessary to create pulses of distinct amplitudes at various *SOC* states (20%, 50% and 80%). In these states, pulses of 10 s duration may be made both in the charge as well as the discharge. In the case of electric vehicles, the amplitudes are C/3, 1C, 2C, 5C and the maximum current established by the manufacturer. Between each pulse, it is necessary to allow 10 minutes of rest time [5], although some authors have also proposed improved versions of the pulse tests [3].

C. *Open circuit voltage characterization*

This type of tests attempts to establish the relationship between the V_{OC} and the *SOC*. This voltage is fundamental in order to develop electric models of batteries, the majority of the models presented in the literature are based on the $V_{OC}(SOC)$ dependency in an attempt to model and predict the battery's behavior [1], [12]. This parameter is also dependent on the temperature. Unlike capacity and internal resistance, the $V_{OC}(SOC)$ relationship is generally considered to be constant throughout a cell's service life [13].

When it comes to measuring V_{OC}, it is necessary to pay special attention to the possible effects of hysteresis that may occur in this type of test. So, based on whether or not the measurement is obtained during charging or discharging, the V_{OC} value may vary. This phenomenon is of special relevance in the $LiFePO_4$-type Li-ion cells; however, in the NMC type, it rarely appears.

Two methods have been widely used to characterize V_{OC}. The first is the so-called galvanostatic intermittent titration technique (GITT). This method consists of applying a constant charge or discharge current until reaching the desired *SOC* state. Then, it is allowed to rest for a certain period so that the cell may be stabilized. One of the most frequently discussed parameters is the resting time required to ensure cell stabilization [13]; this work, however, does not analyze this function, nor does it calculate the time constant for these purposes. For example, some authors have conducted tests at a C-rate of C/2 followed by a 3 h rest period [2], while others have worked with a C-rate of C/6 followed by a 1 h rest [3].

Another topic that is often considered with regards to this technique is the ΔSOC (%) necessary in order to obtain sufficient points to faithfully reproduce the real curve [13]. At a lower ΔSOC (%), the precision is increased, since more points are obtained to create the $V_{OC}(SOC)$ relationship. However, both an increase in rest time and a reduction in ΔSOC (%) lead to a significant increase in the time needed to characterize the cell. For example, if ΔSOC steps of 5% at 1C are made, followed by a rest period of 40 h, to ensure the stabilization both in charging and discharging, the test would take several months to complete. This is not realistic for either manufacturers or researchers. However, if the rest time is

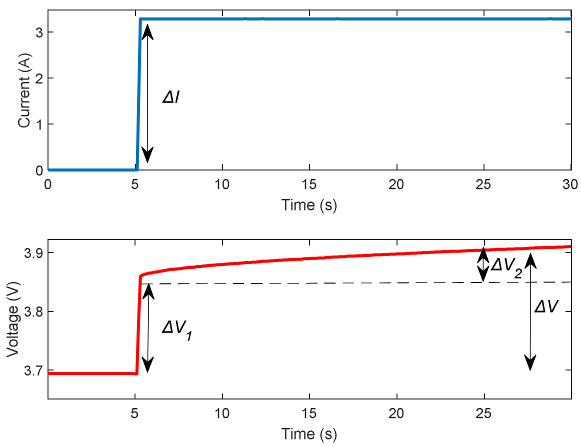

Fig. 1. A current pulse of 1C applied to a 3350 mAh 18650 Li-ion cell.

reduced to 1 hour, maintaining the other testing conditions, the total test time may be reduced to less than two days.

The second method, known as the pseudo-V_{OC} test, consists of making a discharge and a charge at very low current values. Thus, the decrease in voltage that is associated with the internal resistance is practically negligible. Furthermore, it is considered that, given the low currents, R_i barely generates heat, therefore constant temperatures may be assumed. In this type of tests, the working current that is most commonly found in the literature is C/25 [13].

III. Experimental tests and Results

For the experimental study conducted in this work, we used 18650 Li-ion cells having similar characteristics to those of some of the principal global manufacturers. Specifically, the Samsung INR18650 30Q [6], LG 18650 HG2 [7] and Panasonic NCR18650 B [8] models were used. For each model, 2 cells were characterized, in order to reduce the dispersion associated with the manufacturing processes.

The Samsung INR18650 30Q cells have a nominal capacity of 2950 mAh, with a maximum discharge current of 15 A. The LG 18650 HG2 cells have a nominal capacity of 3000 mAh and a maximum discharge current of 20 A, whereas the nominal capacity of the Panasonic NCR18650 B cells is 3350 mAh with a maximum discharge current of 6.7 A. In all of these, the capacity refers to a discharge current of C/5 and a room temperature of 20–25ºC, and the voltage operating range for all of these is 2.5–4.2 V.

All of the tests were conducted in an environment having a controlled temperature of 25ºC, using a climatic chamber to ensure said temperature. Furthermore, for cell temperature monitoring, NTC sensors were used. Each sensor was attached to the center of each cell, using foam tape to ensure the proper measurement of the surface temperature and to prevent the impact of the environmental temperature on the measurement. Finally, controlled cell charge and discharge, as well as the distinct electrical tests were carried out using a multi-channel battery tester, as shown in Fig. 2.

A. Capacity test

A variety of tests were carried out to determine how the distinct characterization methods affected the capacity measurement. For this, discharges were made at distinct C-rates, revealing the results obtained both with and without the CV phase at the end of the discharge. To prevent the potential aging affect, only CCCV discharge tests were conducted, from which it was possible to easily obtain the value that would have been obtained from an exclusively CC discharge.

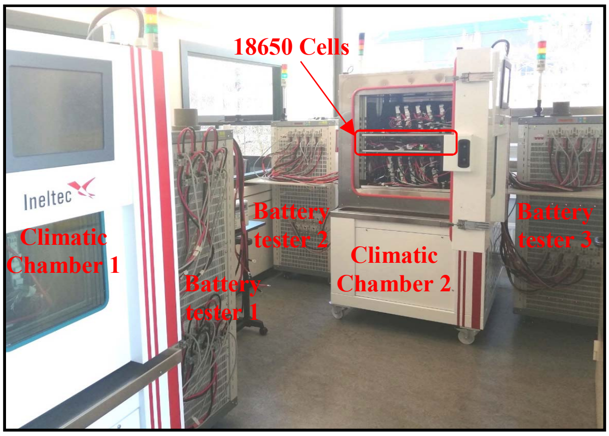

Fig. 2. Test bench used for cell characterization.

All of the charges were carried out identically, that is, at a C-rate of C/3 to 4.2 V followed by a CV phase with an ending current of C/20. The order of the discharge currents was selected at random, in order to ensure an improved comparative (see Table I). The discharge phase at a constant voltage begins when a value of 2.5 V is reached and ends when the current decreases below C/20. It is important to note that in the Panasonic NCR18650 B cells, discharges at 5C were avoided, based on manufacturer recommendations.

TABLE I. From left to right, the order of the discharge C-rate followed by each cell

Cell type	Discharge C-rate					
Samsung (SAM 1)	C/5	3C	C/2	1C	2C	5C
Samsung (SAM 2)	C/5	1C	3C	5C	2C	C/2
LG 1	5C	1C	C/5	C/2	2C	3C
LG 2	C/2	2C	1C	5C	3C	C/5
Panasonic (PAN 1)	C/2	2C	3C	C/5	1C	-
Panasonic (PAN 2)	2C	3C	C/5	C/2	1C	-

The results obtained are shown in Fig. 3. It is of special note that the maximum capacity is achieved with the highest C-rate discharge values. This is mainly related to the influence of the temperature on capacity. Once the discharge phase is reached at a constant voltage, the operating temperature of the cell increases slightly as the discharge current increases. So, higher operating temperatures have a catalytic effect on the electrochemical reactions and increase cell capacity. The temperature value represented in Fig. 3 corresponds to the measurement obtained at the time of the completion of the CC discharge and the start of the CV.

Another significant aspect of the results shown in Fig. 3 is the difference in the capacity measurement based on the C-rate of discharge and the methodology used for its characterization. In CC discharges, as recognized in the literature, as the C-rate increases, the capacity obtained decreases; however, in the CCCV discharges, the behavior is contrary to the expected. Although this increase in capacity may be due to the increase in operating temperature, further research is necessary.

Given the particular results obtained in the discharge at C/5 of the LG 2 cell, where a greater capacity measurement was expected, and in the discharge at 3C of the PAN 2 cell, where the capacity measurement is particularly low, it was decided that these tests would be repeated after allowing one day of rest for both cells. The results obtained for the two cells did not differ from those that were found before.

Of the results that were obtained, it may be deduced that the disparity in the capacity measurement cannot be avoided by characterizing cells at low current values. However, as the working current increases, so does the dispersion of the temperature, therefore it is recommended that work be carried out at low current values, below C/2, to ensure that the functioning temperature is similar to the room temperature.

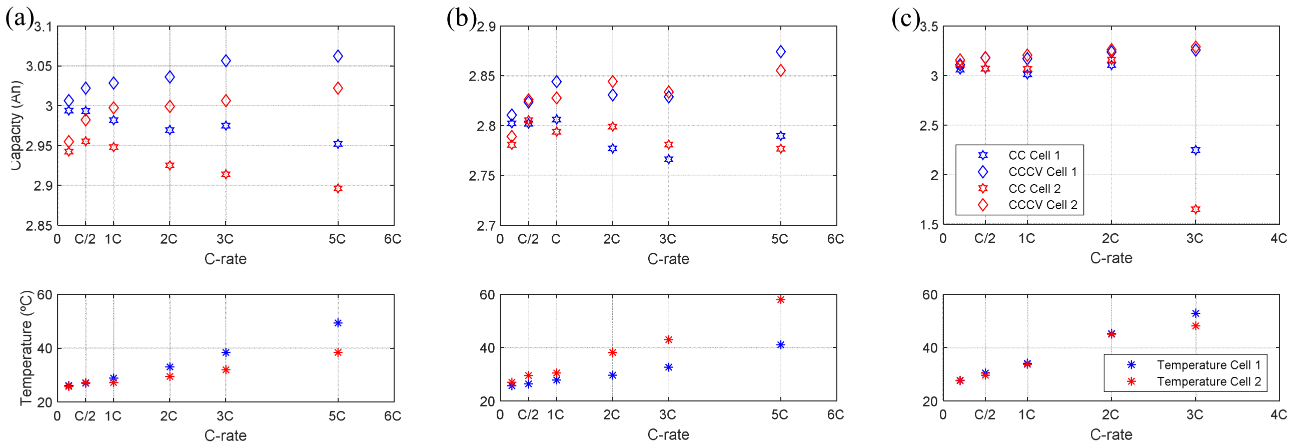

Fig. 3. Measurement of capacity obtained for distinct C rates and distinct characterization methods. (a) SAM cells, (b) LG cells, (c) PAN cells.

However, this analysis should be carried out in a study with a larger population.

B. Open voltage circuit test

As previously explained, two main methods are used to establish the $V_{OC}(SOC)$ dependency. In this work, the results obtained from both methods in the distinct tests are compared.

To verify the effects of the distinct decisions on the characterization of the open circuit voltage, the following three test methodologies have been proposed: In methodology 1, constant current discharges were made at C/6 followed by a rest time of 1h. Methodology 2 consists of a rest periods of 3 h, achieved through steps of a larger current, C/2. For both cases, the ΔSOC is 10%, both in the charge as well as the discharge. When beginning the test, the cell is always discharged with a constant current of C/3 at a voltage of 2.5 V. Then, it is charged at the same C-rate, followed by a constant charge state of 4.2 V, until the current reaches a minimum value of C/20. In this way, the initial cell state is homogenized. Finally, methodology 3 consists of a pseudo V_{OC} test at a C-rate of C/25. Despite the simplicity of this test, its use has not been very extensive, mainly due to the extensive time required to complete the characterization, in this case, a minimum of 50 h.

Fig. 4 reveals the distinct values of V_{OC} that have been obtained for each case, for each methodology. In the graphic representation, only one cell has been included per manufacturer, to facilitate reader visualization. Previously, the differences obtained in cells of the same manufacturer have been compared, finding these differences to be minimal. As for the times required to complete each test, method 1 requires approximately 32 h, method 2 approximately 68 h and method 3 approximately 50 h.

Generally, $V_{OC}(SOC)$ relationship is fitted by means of n degree polynomial or spline function. In order to define the degree of the polynomial the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) have been chosen. Table II shows the optimal degree of the polynomial corresponding to both AIC and BIC, the value of R-square concerns the quality of the fitting in the polynomial of lowest degree. These information criterions allow choosing between different models taking into account the goodness of the fit and avoiding an excessive polynomial degree.

TABLE II. POLYNOMIAL FITTING DEGREE ACCORDING TO AIC AND BIC

	Method 1			Method 2			Method 3		
Cell type	AIC	BIC	R^2	AIC	BIC	R^2	AIC	BIC	R^2
SAM1	7	5	0.992	7	7	0.992	11	11	0.987
SAM2	7	5	0.992	7	5	0.993	11	11	0.972
LG1	7	7	0.998	7	7	0.998	11	11	0.98
LG2	7	7	0.998	10	7	0.998	11	11	0.98
PAN1	10	9	0.999	9	9	0.999	11	11	0.983
PAN2	10	9	0.999	9	9	0.999	11	11	0.983

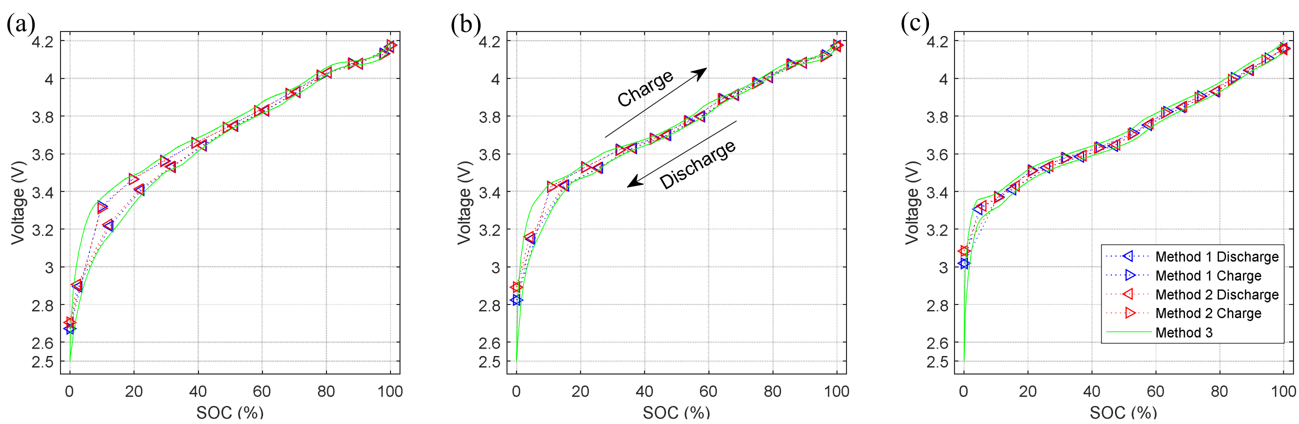

Fig. 4. Open circuit voltage via distinct methods. Right-pointing triangles mean charge and left-pointing discharge (a) SAM1 cell, (b) LG1 cell, (c) PAN1 cell.

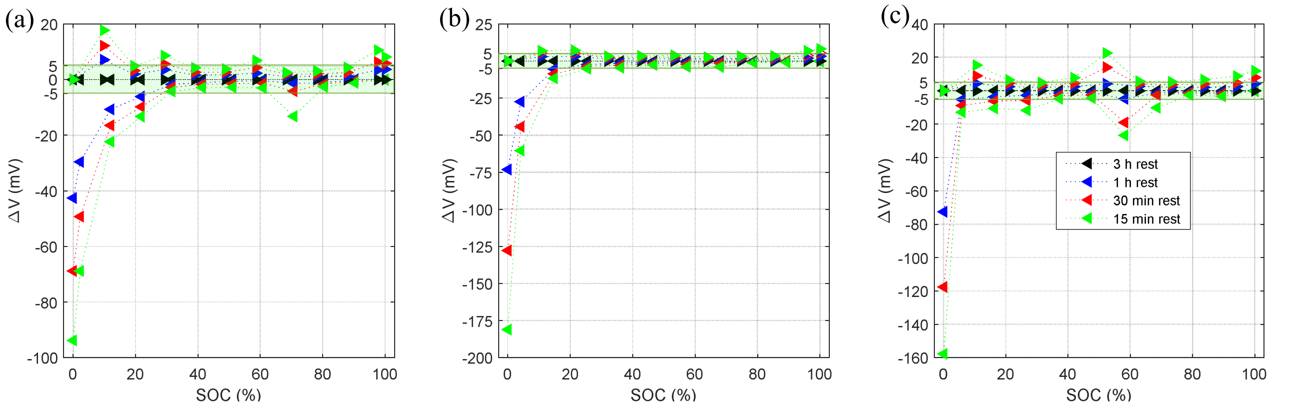

Fig. 5. Voltage recovery for different rest times. Right-pointing triangles mean charge and left-pointing discharge, (a) SAM1 cell, (b) LG1 cell, (c) PAN1 cell.

For the analysis of the influence of the increase of rest on the V_{OC} measurement, it was considered that at 3 hours, the stabilization was complete, and as of this measurement, it was possible to calculate the error that would occur if the rest period was shorter. In Fig. 5, it is seen that with a rest period of one hour, the voltage falls within the range of ±5 mV. However, for values of *SOC* that are below 20%, the deviation increased significantly. Generally, manufacturers recommend SOC_{min} and SOC_{max} operating thresholds. If these values are exceeded, the service life may be dramatically reduced. A typical SOC_{min} value is 10%. If excluding this region from the results shown in Fig. 5, the maximum deviation to be used would be below 10 mV.

One of the advantages of using the GITT technique is that it includes current steps. These steps are preceded by a considerably high stabilization period; therefore, they are similar to those carried out in the *Ri* tests. Upon comparing these values with those obtained by the steps in the test that was especially intended to obtain R_i values, almost no difference is found. So, this test not only permits the characterization of V_{OC}, but also the characterization of the internal resistance. In this way, not only does it offer savings in the initial characterization time, but it also contributes to shortening the time and tests needed when conducting routine check-ups.

Similarly, using this procedure, it is possible to obtain a capacity measurement for a discharge by pulse profile. Although this value is not common in referring to the nominal capacity of the cell, it may be quite useful, especially in research that seeks to study aging, be it due to a loss of capacity under the same conditions or due to the increase in internal resistance. Therefore, it also contributes to reducing the time needed for routine check-ups and is less of an interference when carrying out aging tests.

C. Internal resistance test

The IEC62660-1 standard was considered for the tests necessary to obtain the R_i. In this work, the standard was followed, although instead of the three previously mentioned *SOC* states (from Section II), variations of the 10% of the *SOC* were used, achieving a C-rate of C/3 as the standard indicates. This process was repeated both in the charging as well as in the discharging at a room temperature of 25ºC. The pulses were made in a *SOC* range of between 20% and 80% to avoid exceeding the (maximum or minimum) voltage values during large pulses.

The results indicate that a greater R_i value was obtained when the pulses were made at low currents. This phenomenon may be due to a higher internal cell temperature, associated with the high current value. It is also found that the R_i values are greater if the discharge pulse is made during the general discharge process, whereas during the charging process, the R_i value is greater if it a charge pulse is made.

The results are shown in Fig. 6 (a). The dashed line represents the R_i values obtained from method 2 presented in the open circuit voltage technique as explained above. The pulses are done with a C/2 rate preceded by a rest of 3 h. If

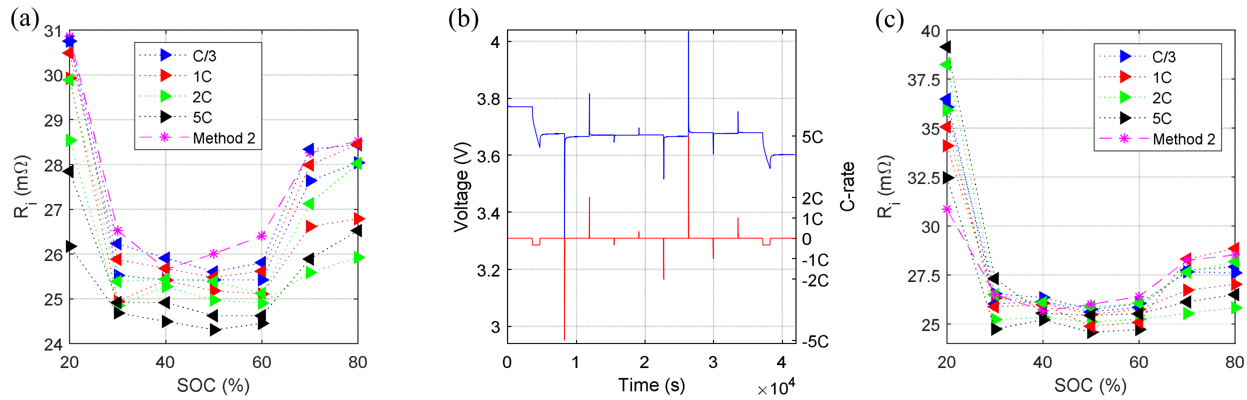

Fig. 6. R_i values of LG1 cell via distinct C-rate (a) R_i values following the IEC62660-1 standard during a general discharge (b) Proposed random test, blue line represents voltage and red line current (c) R_i values following the random test during a general discharge. Right-pointing triangles mean charge pulse and left-pointing discharge pulse.

this technique is used, the information obtained concerning the value of R_i fits in all the operation range of the cell. However, if the standard test is used for this purpose, it is only valid for a range of 20–80% of the *SOC*. Furthermore, if the current value is too high during the pulse, the maximum and minimum voltage limits can be exceeded. In order to avoid those critical operation points, a cut-off limit was set during the test. As it can be seen in Fig. 6 (a), it was impossible to perform high current charging pulses during the 60% and 70% state of charge.

In order to analyse the influence of the sequence of the current pulsed proposed in the IEC62660-1standard, a test with a random order was performed, as shown in Fig. 6 (b). The results obtained following this procedure did not significantly differ from the ones of the standard test, and a similar tendency is observed, as represented in Fig. 6 (c). However, a larger value of R_i is achieved at low *SOC*. This fact is caused by the high current discharge made in the first place. The pulse caused a voltage drop of 0.1 V, in low *SOC* this voltage drop supposes a reduction of the *SOC* of 10%, as it can be seen in Fig. 4. Therefore, in that point, the test was not conducted under the same operation parameters.

IV. CONCLUSION

This work compares some of the most common methods described in the bibliography, for the characterization of Li-ion cells. To do this, three models of 18650 Li-ion cells manufactured by Samsung, LG and Panasonic were used. Based on the results, the following conclusions were obtained.

In capacity tests, it is recommended that C-rates equal to or lower than C/3 are used, since at higher currents, the surface temperature of the cell increases slightly. This thermal gradient has been found to be quite disparate within the cells of a same population. Thus, the capacity results may vary considerably for cells of the same manufacturer when using high current values. This is accentuated in the CCCV discharges where the CV discharge phase is carried out at high temperatures, thereby leading to an overestimation of the capacity value. Although this increase in capacity may be initially attributed to temperature, it is necessary to examine this aspect in greater detail.

The internal resistance test may be damaging to the cell, introducing degradation processes, given the excessive voltages (exceeding manufacturer recommendations) that are used. Furthermore, this method may considerably alter the results obtained in an aging test, since when used as a routine check-up, it may contribute to the accelerated cell deterioration. As the cell ages, its internal resistance increases, therefore these problems are more accentuated. Thus, it is recommended that this method is avoided, especially in characterizations of second life cells or those that have already suffered from deterioration given that their internal resistance is greater than the initial resistance.

Finally, in the three methods that have been used to characterize the open circuit voltage, the results were quite similar. The main difference lies in the time used to conclude the test. For example, in the calendar aging tests, in which work is typically carried out at high temperatures, an excessively long check-up time could negatively affect the obtained results. Furthermore, the saving of time was fundamental for both researchers and manufacturers. Therefore, and based on the results obtained, carrying out the one-hour GITT test was proposed as the best solution. This reduced the time needed to carry out the test by approximately 50%. Through the GITT test characterization, diverse current steps were carried out, permitting the obtaining of the R_i value. These steps were preceded by a longer stabilization time than those proposed in the IEC 62660-1 standard. Given that the steps were always carried out in the same charging or discharging sequence, it was possible to ensure that the voltage thresholds established by the manufacturer would not be exceeded during the pulse. The R_i is characterized in a range of 0% to 100% of the *SOC,* instead of 20% to 80%. Therefore, these tests are ideal for routine check-ups. Although the capacity measure is not typically treated with voltage pulses, but rather, with constant discharges, it contains the information required to analyze the capacity fade in the distinct aging tests, assuming that the test is always conducted under similar conditions.

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